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Single-frequency, Yb-free, resonantly cladding-pumped large mode area Er fiber amplifier for power scaling

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We report results for a single-frequency (SF) resonantly cladding-pumped Yb-free large mode area (LMA) erbium-doped fiber amplifier (EDFA) with nearly 50% slope efficiency based on a commercial 20/125 μm Er-doped double-clad LMA fiber with a core numerical aperture of 0.07. We believe that this is the original demonstration of a SF resonantly cladding-pumped LMA EDFA. We obtained a diffraction-limited SF output of 9.3 W, which is also a record power output obtained for resonantly cladding-pumped LMA EDFA. © *2008 American Institute of Physics*.
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Recent advances in eye-safe 1.5 μm Yb–Er-doped fiber lasers (utilizing Yb–Er energy transfer for Er excitation by highly developed 9XX nm diode pumps) are quite impressive, and further power scaling from a single-fiber laser is expected. There has been substantial speculation that fibers, unlike bulk solid-state lasers, are nearly immune to effects associated with heat deposition in the gain medium and that power scaling in fibers is therefore limited only by nonlinear effects, e.g., stimulated Brillouin scattering and stimulated Raman scattering. However, realistic analysis of Er-doped fiber laser power scaling based on previously reported data[1,2] indicates that heat generation associated with (i) inefficiencies of Yb-Er energy transfer and (ii) the quantum defect in Yb–free erbium-doped fiber amplifiers (EDFAs) pumped at 9XX nm is still sufficiently detrimental that fibers may reach fracture limits before nonlinear scaling limits. Thus, fiber laser approaches providing the minimum heat deposition in the fiber are the most promising for ultimate power scaling. Our recent experiments with resonantly pumped eye-safe (1.5–1.6 μm) bulk solid-state lasers[3,4] point to the significant power-scaling potential of direct resonant pumping of Er (into its upper laser manifold $^4I_{13/2}$) compared to 9XX nm pumping of Yb–Er codoped lasers (into the upper Yb^{3+} laser manifold $^4F_{5/2}$ with the subsequent energy transfer to the $^4I_{11/2}$ manifold of Er^{3+} ion) as well as 9XX nm pumping (into $^4I_{11/2}$ manifold) of Er-only doped (Yb-free) lasers. For fibers, this approach was first demonstrated by Snitzer.[5] With this pumping approach heat deposition would predominantly be associated with very low quantum defect (5% and less), and, therefore, this approach is much more amenable to power scaling.

Another important step toward resonantly pumped Er-doped fiber laser power scaling is the cladding pumping technique. Significant successes have been demonstrated in fiber laser resonantly core-pumped Er-fiber lasers,[6] but only cladding pumping is amenable to utilizing the most powerful (although low brightness) highly multimode fiber-coupled long-wavelength (14XX–15XX nm) InGaAsP/InP diodes and bars as a pump source for achieving high powers. So far, very few efforts have been reported on the scaling of resonantly cladding diode-pumped Yb-free Er fiber lasers to power levels well beyond those of telecommunication amplifiers, in which InGaAsP/InP diodes have been used for pumping. Although an output power of ~1 W was achieved in two efforts,[7,8] neither of these addressed amplification of single-frequency (SF) laser radiation, which is most suitable for further power scaling—well beyond single-fiber laser power limits—via subsequent beam combining.[9] Of these two efforts, only one[8] exploited true large mode area (LMA) fiber, which has the highest potential for power scalability.

In this paper, we present characterization results for a SF Yb-free EDFA based on Er-doped commercial-off-the-shelf (COTS) LMA fiber resonantly cladding-pumped by fiber-coupled InGaAsP/InP diode modules. We believe this to be the original demonstration of a SF resonantly cladding-pumped LMA EDFA and the obtained diffraction-limited, SF (single longitudinal mode) output of 9.3 W is a record power for resonantly cladding-pumped LMA EDFA.

Our experimental setup, a fully integrated Er-based master oscillator-power amplifier, is shown in Fig. 1. It is comprised of a variable wavelength SF (spectral width <1 MHz) diode laser seeder with the single-mode *C*-band Er-fiber preamplifier and booster amplifier. The booster amplifier is the subject of this study. The preamplifier provides a maximum output power of ~0.4 W in order to maintain a signal level sufficiently close to saturating the booster gain. The maximum power, and the longest signal wavelength (1570 nm)

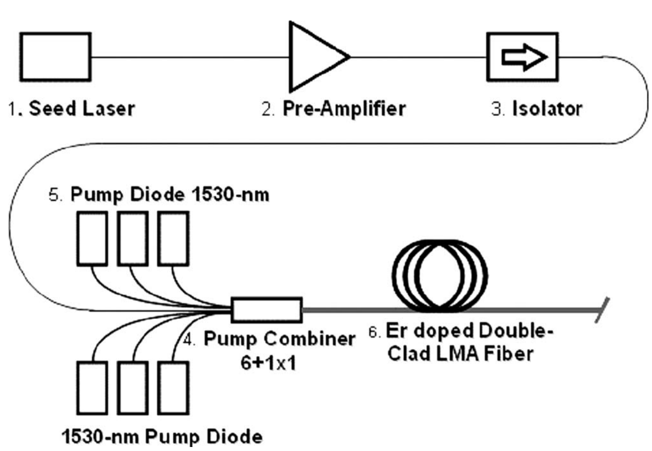

FIG. 1. Experimental layout: SF tunable seed laser, 6 dBm output (1); 0.5 W *C*-band EDFA (2); OFR optical isolator (3); 6+1×1 SIFAM pump combiner (4); 1520–1530 nm 5–6 W fiber-coupled InP diode lasers (5); Liekki Er60-20/125DC fiber (6).

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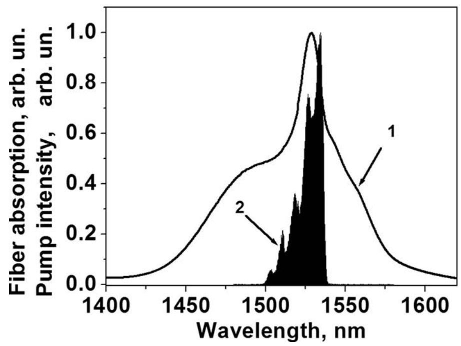

FIG. 2. Combined spectrum of the six 1530 nm fiber-coupled laser diode modules at 27 W of output power (curve 2) overlaid with the Er60-20/125DC fiber absorption (curve 1).

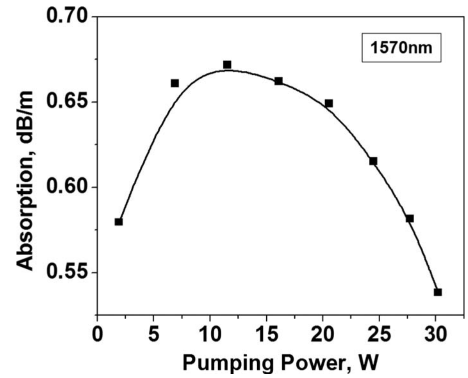

FIG. 3. Er60-20/125DC fiber absorption vs pump power in the presence of ~400 mW of 1570 nm seed radiation.

were both limited by the available *C*-band preamplifier. The Yb-free fiber booster amplifier is based on a ~9.5 m standard (COTS) Liekki Er 60-20/125DC LMA fiber with a core numerical aperture (NA) of 0.07. The fiber length was chosen based on simulation results. The gain fiber was coiled to a diameter of ~4 cm in order to preserve the near-diffraction-limited amplifier output beam quality. Fiber-coupled optical isolators were used to integrate the seeder with the preamplifier, and the preamplifier with the booster amplifier, while suppressing detrimental interstage feedbacks. The booster amplifier was cladding copumped by six ~5–6 W fiber-coupled (105/125 μm, NA of 0.15) InGaAsP/InP laser diode modules coupled into Er 60-20/125DC LMA fiber via a $(6+1)\times 1$ SIFAM pump combiner. The pump combiner transmitted 89% of the pump power at the pump wavelengths, and the maximum combined launched power was measured to be 30.2 W. All six pump diode modules were mounted on a common cold plate for conductive cooling without active stabilization of their individual temperatures. The individual pump diode lasers were not preselected for a specific spectral position. Ideally, they should all have provided pump power in the wavelength range around 1530 nm to match the absorption peak for Er-doped fiber (see Fig. 2, curve 1). However, all diode modules were operated at the same temperature, and their peak wavelengths exhibited some variation. As a result, the collective spectral width of pumping radiation coupled into the booster fiber was about 20 nm full width at half maximum (see Fig. 2, curve 2). According to Liekki (and as confirmed by our spectroscopic measurements), a clad absorption coefficient of about 1.5 dB/m is expected for ~1530 nm pumping. For our broadband pumping source, we measured the absorption versus pump power in the presence of ~400 mW of 1570 nm seed signal. The measured dependence is presented in Fig. 3. As can be seen, the effective absorption was found to be in the range of only 0.52–0.67 dB/m. Considering the presence of the seed (used in order to minimize possible pump saturation effects), we believe the main reason for this smaller absorption efficiency was the excessively broadband nature of the pump source used in this first experiment. It is also important to note that the temperature adjustment of the pump spectrum center of gravity (to maximize absorption) was accomplished for the "midrange" currents. Because the pump diode coolant temperature was maintained at the same value during the entire experiment, the actual diode temperature shifted with variations in the pump current. The absorption fall-off outside the "midrange currents" in Fig. 3 is due the temperature-driven shifts of the central wavelength of the pump spectrum to nonoptimal values that occurred with pump current variation.

The performance of the Er 60-20/125DC LMA fiber amplifier was studied at seed wavelengths of 1560, 1565, and 1570 nm. The SF nature of the output power after the preamplifier and the booster amplifier was monitored throughout the experiment. The measured dependence of SF output power on absorbed power is indicated in Fig. 4. With a seed wavelength of 1570 nm, the fiber amplifier demonstrated a maximum conversion efficiency of 46% with respect to absorbed pump power (33% optical-to-optical efficiency). The maximum output power obtained at this wavelength was over 9.3 W. We observed no output power saturation with increasing pump power within the limits of our measurement. We could detect neither nonlinear effects nor amplified spontaneous emission (ASE) power, which could possibly limit the amplifier performance. Therefore, we believe that the observed output power is limited only by pump power. According to our estimates, even with the same pump power, the output power can be significantly increased by (i) utilizing a "co- plus counter-pumping" scheme with longer fiber length, (ii) optimizing the seeder wavelength toward the expected 1585–1590 nm gain maximum, and (iii) increasing the preamplifier power (which is currently limited by the available *C*-band preamplifier). It is also estimated that the obtained slope efficiency is likely to be affected by Er^{3+} upconversion effects in highly concentrated 60-20/125DC LMA fiber.

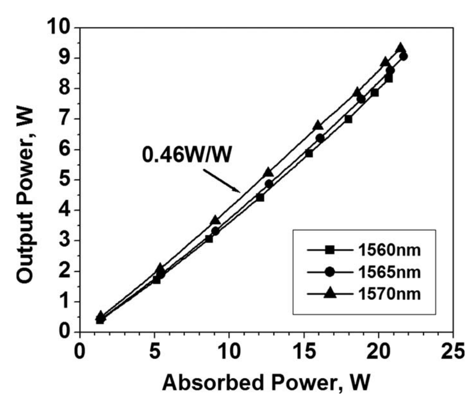

FIG. 4. Single-frequency/single-mode output power of the Yb-free COTS Er60-20/125 cladding-pumped (at 1530 nm) EDFA booster vs absorbed pump power with the fixed preamplifier output of ~0.4 W at three different seeder wavelength (indicated on the inset).

In summary, we report characterization results of a SF Yb-free resonantly cladding-pumped COTS Er60-20/125DC LMA fiber amplifier. The nearly diffraction-limited SF output power of 9.3 W obtained from this amplifier is believed to be the highest power reported to date for resonantly cladding-pumped LMA EDFA. The measured slope efficiency of 46% with respect to absorbed pump power was limited by the available seeder/preamplifier wavelength range and power. Our current results are an important confirmation of the significant power-scaling potential of the Yb-free Er-fiber laser in a resonantly cladding-pumped implementation, and significant improvements in maximum power and slope efficiency are expected with further system optimization.

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